Introduction to Quantum Computer Science and Applications

Exercise Sheet 7

Exercise 1 (A proof useful for CSS codes)**.** *Our aim in this exercise is to prove*

$$\mathbf{H}^{\otimes n} |\mathcal{C}\rangle = |\mathcal{C}^{\perp}\rangle$$

where $\mathcal{C}$ *is a subspace of* $\mathbb{F}_2^n$*,*

$$\mathcal{C}^{\perp} = \left\{ \mathbf{c}^{\perp} \in \mathbb{F}_2^n \; : \; \forall \mathbf{c} \in \mathcal{C}, \; \langle \mathbf{c}, \mathbf{c}^{\perp} \rangle = \sum_{i=1}^{n} c_i c_i^{\perp} = 0 \mod 2 \right\}$$

and

$$|\mathcal{C}\rangle \stackrel{def}{=} \frac{1}{\sqrt{\sharp \mathcal{C}}} \sum_{\mathbf{c} \in \mathcal{C}} |\mathbf{c}\rangle \quad ; \quad |\mathcal{C}^{\perp}\rangle \stackrel{def}{=} \frac{1}{\sqrt{\sharp \mathcal{C}^{\perp}}} \sum_{\mathbf{c}^{\perp} \in \mathcal{C}^{\perp}} |\mathbf{c}^{\perp}\rangle$$

Exercise 2 (Building CSS encoding)**.** *We are given two linear codes* $\mathcal{C}_{\mathbf{X}}$ *and* $\mathcal{C}_{\mathbf{Z}}$ *of length* n *such that* $\mathcal{C}_{\mathbf{Z}} \subseteq \mathcal{C}_{\mathbf{X}} \subseteq \mathbb{F}_2^n$*. Recall that* $\mathcal{C}_{\mathbf{X}}/\mathcal{C}_{\mathbf{Z}}$ *is a subspace defined as*

$$\mathcal{C}_{\mathbf{X}}/\mathcal{C}_{\mathbf{Z}} = \{ \overline{\mathbf{x}} \; : \; \mathbf{x} \in \mathcal{C}_{\mathbf{X}} \} \quad \textit{where} \;\; \overline{\mathbf{x}} \stackrel{def}{=} \mathbf{x} + \mathcal{C}_{\mathbf{Z}} = \{ \mathbf{x} + \mathbf{c}_{\mathbf{Z}} \; : \; \mathbf{c}_{\mathbf{Z}} \in \mathcal{C}_{\mathbf{Z}} \} \subseteq \mathcal{C}_{\mathbf{X}}$$

Let,

$$k \stackrel{def}{=} \dim \mathcal{C}_{\mathbf{X}}/\mathcal{C}_{\mathbf{Z}} = \dim \mathcal{C}_{\mathbf{X}} - \dim \mathcal{C}_{\mathbf{Z}}$$

Recall that

$$\mathcal{C}_{\mathbf{X}}/\mathcal{C}_{\mathbf{Z}} = \left\{ \mathbf{x}_i + \mathcal{C}_{\mathbf{Z}} \; : \; 1 \leq i \leq 2^k \right\} \quad \textit{and} \quad \mathcal{C}_{\mathbf{X}} = \bigsqcup_{1 \leq i \leq 2^k} \mathbf{x}_i + \mathcal{C}_{\mathbf{Z}}$$

for 2^k *vectors* $\mathbf{x}_i \in \mathcal{C}_{\mathbf{X}}$ *which are called the representatives of* $\mathcal{C}_{\mathbf{X}}/\mathcal{C}_{\mathbf{Z}}$*.*

1. *Show how to efficiently compute the following mappings (we naturally identify* $\mathbf{i} \in \mathbb{F}_2^k$ *to an integer* $1 \leq i \leq 2^k$*)*

$$\mathbf{i} \in \mathbb{F}_2^k \longmapsto \mathbf{x}_i \in \mathbb{F}_2^n, \quad \mathbf{x}_i \in \mathbb{F}_2^n \longmapsto \mathbf{i} \in \mathbb{F}_2^k$$

$$\mathbf{y} \in \mathcal{C}_{\mathbf{X}} \mapsto \mathbf{x}_i \quad \textit{when } \mathbf{y} \in \mathbf{x}_i + \mathcal{C}_{\mathbf{Z}}$$

   Notice that the first two mappings "fix" a choice of representatives $\mathbf{x}_i$*'s; recall that if* $\{\mathbf{x}_i \; : \; 1 \leq i \leq 2^k\}$ *is a set of representatives of* $\mathcal{C}_{\mathbf{X}}$*, then* $\{\mathbf{x}_i + \mathbf{c}_i \; : \mathbf{c}_i \in \mathcal{C}_{\mathbf{Z}} \text{ and } 1 \leq i \leq 2^k\}$ *is also a set of representatives. The last mapping is well defined by the decomposition of* $\mathcal{C}_{\mathbf{X}}$ *as disjoint union of cosets.*

2. *Show how to compute* $|\mathbf{x}\rangle\,|\mathbf{x}+\mathcal{C}_\mathbf{Z}\rangle$ *where*

$$|\mathbf{x}+\mathcal{C}_\mathbf{Z}\rangle \stackrel{def}{=} \frac{1}{\sqrt{\sharp\mathcal{C}_\mathbf{Z}}}\sum_{\mathbf{y}\in\mathcal{C}_\mathbf{Z}} |\mathbf{x}+\mathbf{y}\rangle\,.$$

   and supposing that we have access to $|\mathbf{x}\rangle$.

   Hint: *use the matrix* $\mathbf{G}\in\mathbb{F}_2^{k_\mathbf{Z}\times n}$ *(*$k_\mathbf{Z} \stackrel{def}{=} \dim \mathcal{C}_\mathbf{Z}$*) whose rows form a basis of* $\mathcal{C}_\mathbf{Z}$ *(which is supposed to be given to have a description of* $\mathcal{C}_\mathbf{Z}$*); recall that*

$$\mathcal{C}_\mathbf{Z} = \left\{ \mathbf{mG} \;:\; \mathbf{m}\in\mathbb{F}_2^{k_\mathbf{Z}} \right\}$$

3. *Deduce how to implement the following* CSS *encoding:*

$$\sum_{\mathbf{i}\in\{0,1\}^k} \alpha_\mathbf{i} \underbrace{|\mathbf{i}\rangle}_{k \text{ qubits}} \longmapsto \sum_{\mathbf{x}_i} \alpha_\mathbf{i} \underbrace{|\mathbf{x}_i+\mathcal{C}_\mathbf{Z}\rangle}_{n \text{ qubits}}$$

Exercise 3 (Shor's code is a CSS code)**.** *Show that the following codes are* CSS *codes and give* $(\mathcal{C}_\mathbf{Z},\mathcal{C}_\mathbf{X})$ *for them*

1. $\mathrm{Vect}\left(|000\rangle\,,|111\rangle\right)$

2. $\mathrm{Vect}\left((|0\rangle+|1\rangle)^{\otimes 3}\,,(|0\rangle-|1\rangle)^{\otimes 3}\right)$

3. $\mathrm{Vect}\left((|000\rangle+|111\rangle)^{\otimes 3}\,,(|000\rangle-|111\rangle)^{\otimes 3}\right)$

Exercise 4 (Steane's code)**.** *Let* $\mathcal{C}$ *be the* $[7,4,3]$ *Hamming code (that we have seen during the lecture). Recall that it has parity-check matrix*

$$\mathbf{H} \stackrel{def}{=} \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{pmatrix}.$$

Let $\mathcal{C}_\mathbf{X} \stackrel{def}{=} \mathcal{C}$ *and* $\mathcal{C}_\mathbf{Z} \stackrel{def}{=} \mathcal{C}^\perp$.

1. *Show that* $\mathbf{H}\mathbf{H}^\top = \mathbf{0}$.

2. *Deduce that* $\mathcal{C}_\mathbf{Z} \subseteq \mathcal{C}_\mathbf{X}$.

3. *From the above question,* $(\mathcal{C}_{\mathbf{Z}}, \mathcal{C}_{\mathbf{X}})$ *defines a* CSS*-code. How many qubits does it enable to encode? How many errors can it correct?*

Exercise 5 (CSS codes are stabilizer codes)**.** *Let* $\mathcal{C}_{\mathbf{X}}$ *and* $\mathcal{C}_{\mathbf{Z}}$ *be two linear code such that* $\mathcal{C}_{\mathbf{Z}} \subseteq \mathcal{C}_{\mathbf{X}}$.

1. *Show that for all* $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{C}_{\mathbf{Z}}$, $\mathbf{f}_1, \mathbf{f}_2 \in \mathcal{C}_{\mathbf{X}}^{\perp}$ *we have*
$$\left(\mathbf{X}^{\mathbf{e}_1}\mathbf{Z}^{\mathbf{f}_1}\right)\left(\mathbf{X}^{\mathbf{e}_2}\mathbf{Z}^{\mathbf{f}_2}\right) = \left(\mathbf{X}^{\mathbf{e}_2}\mathbf{Z}^{\mathbf{f}_2}\right)\left(\mathbf{X}^{\mathbf{e}_1}\mathbf{Z}^{\mathbf{f}_1}\right)$$

2. *Show that for any* $\mathbf{e} \in \mathcal{C}_{\mathbf{Z}}$, $\mathbf{f} \in \mathcal{C}_{\mathbf{X}}^{\perp}$, *and* $|\psi\rangle$ *belonging to the* CSS *code given by* $(\mathcal{C}_{\mathbf{X}}, \mathcal{C}_{\mathbf{Z}})$, *we have*
$$\mathbf{Z}^{\mathbf{f}}\mathbf{X}^{\mathbf{e}} |\psi\rangle = |\psi\rangle$$

3. *Deduce that any* CSS *code is a stabilizer code and precise the subgroup of* $\mathbb{G}_n$ *which stabilizes it, in particular, give its description in terms of* $(\mathcal{C}_{\mathbf{X}}, \mathcal{C}_{\mathbf{Z}})$ *(up to an isomorphism).*

Exercise 6 (A 5 qubits code)**.** *Let*

$$\begin{aligned}
\mathbf{M}_1 &= \mathbf{X} \otimes \mathbf{Z} \otimes \mathbf{Z} \otimes \mathbf{X} \otimes \mathbf{I} \\
\mathbf{M}_2 &= \mathbf{I} \otimes \mathbf{X} \otimes \mathbf{Z} \otimes \mathbf{Z} \otimes \mathbf{X} \\
\mathbf{M}_3 &= \mathbf{X} \otimes \mathbf{I} \otimes \mathbf{X} \otimes \mathbf{Z} \otimes \mathbf{Z} \\
\mathbf{M}_4 &= \mathbf{Z} \otimes \mathbf{X} \otimes \mathbf{I} \otimes \mathbf{X} \otimes \mathbf{Z}
\end{aligned}$$

Consider the stabilizer code associated to

$$\mathbb{S} \stackrel{def}{=} \langle \mathbf{M}_1, \mathbf{M}_2, \mathbf{M}_3, \mathbf{M}_4 \rangle$$

1. *Show that every error in* $\mathbb{G}_5$ *of weight* 1 *or* 2 *has a syndrome* $\neq \mathbf{0}$.

2. *Find a harmful error (type B) of weight* 3.

3. *How many errors can be corrected by such a code?*

4. *In which "sense" is this code better than Steane's code?*

Exercise 7 (Minimum distance out of 2 for linear codes). *Let $\mathcal{C} \subseteq \mathbb{F}_2^n$ be a linear code. Recall that its minimum distance d is defined as*

$$d \stackrel{def}{=} \min\left(|\mathbf{c}| \ : \ \mathbf{c} \in \mathcal{C} \backslash \{\mathbf{0}\}\right)$$

where $|\cdot|$ denotes the Hamming weight, namely

$$\forall \mathbf{x} \in \mathbb{F}_2^n, \quad |\mathbf{x}| = \sharp \left\{ i \in [\![1, n]\!], \ x_i \neq 0 \right\}.$$

Let $\mathbf{H} \in \mathbb{F}_2^{(n-k)\times n}$ be a parity-check matrix of $\mathcal{C}$, namely $\mathcal{C} = \left\{ \mathbf{c} \in \mathbb{F}_2^n \ : \ \mathbf{H}\mathbf{c}^\top = \mathbf{0} \right\}$. Show that

$$\forall \mathbf{e}_1, \mathbf{e}_2 \in \mathbb{F}_2^n : \ \mathbf{e}_1 \neq \mathbf{e}_2 \ \text{ and } \ |\mathbf{e}_1|, |\mathbf{e}_2| < \frac{d}{2} \implies \mathbf{H}\mathbf{e}_1^\top \neq \mathbf{H}\mathbf{e}_2^\top$$

Exercise 8 (Gilbert-Varshamov' bound for linear error correcting codes). *We assume here that a linear code $\mathcal{C}$ of length n is drawn at random by choosing an $(n-k) \times n$ parity-check matrix $\mathbf{H}$ for it uniformly at random.*

1. *Let $\mathbf{x} \in \mathbb{F}_2^n \backslash \{\mathbf{0}\}$. Compute $\mathbb{P}\left(\mathbf{x} \in \mathcal{C}\right)$.*
2. *Compute $\mathbb{E}(n_t)$ where n_t denotes the number of codewords in $\mathcal{C}$ of weight t.*
3. *What is $\mathbb{E}(n_{\leq t})$ where $n_{\leq t}$ denotes the number of non-zero codewords of weight $\leq t$?*
4. *What can you say when $\mathbb{E}(n_{\leq t}) < 1$?*
5. *Let $h(x) \stackrel{def}{=} -x \log_2(x) - (1-x)\log_2(1-x)$. By using*

$$\sum_{i=1}^{t-1} \binom{n}{i} \leq 2^{nh(t/n)} \tag{1}$$

   which holds whenever $t/n \leq 1/2$, prove that there exists a code of minimum distance $\geq t$ and dimension $\geq k$ as soon as

$$1 - h(t/n) > k/n$$

Comment: it turns out that *almost all* codes of dimension $\geq k$ as minimum distance $\leq t$ as soon as the above condition is true.